On the newly discovered Canes Venatici II dSph galaxy[1]

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ABSTRACT

We report on the detection of variable stars in the Canes Venatici II (CVn II) dwarf spheroidal galaxy, a new satellite of the Milky Way recently discovered by the Sloan Digital Sky Survey. We also present a $V, B-V$ color-magnitude diagram that reaches $V \sim 25.5$ mag, showing the galaxy's main sequence turn off at $V \sim 24.5$ mag and revealing several candidate blue straggler stars. Two RR Lyrae stars have been identified within the half-light radius of CVn II, a

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[1]Based on data collected at the 4.2m William Herschel Telescope at Roche de los Muchachos, Canary Islands, Spain, and at the 2.3m telescope at the Wyoming Infrared Observatory (WIRO) at Mt. Jelm, Wyoming, USA.

fundamental-mode variable (RRab) with period $P_{ab} = 0.743$ days, and a first-overtone (RRc) RR Lyrae star with $P_c = 0.358$ days. The rather long periods of these variables along with their position on the period-amplitude diagram support an Oosterhoff type II classification for CVn II. The average apparent magnitude of the RR Lyrae stars, $\langle V \rangle = 21.48 \pm 0.02$ mag, is used to obtain a precision distance modulus of $\mu_0 = 21.02 \pm 0.06$ mag and a corresponding distance of 160^{+4}_{-5} kpc, for an adopted reddening $E(B-V) = 0.015$ mag.

Subject headings: galaxies: dwarf —galaxies: individual (CVn II) —galaxies: distances —stars: horizontal branch —stars: variables: other —techniques: photometry

1. Introduction

Dwarf spheroidal (dSph) galaxies represent the most numerous class of objects in the Local Group (LG). They are also the most dark-matter dominated ones, thus making them prime candidates to host a large fraction of the mass in the Universe (Mateo 1998) and the most suitable candidates among which to search for the "building blocks" that may have contributed parts of the halos of larger galaxies. In the last couple of years, ten new Milky Way (MW) satellites have been discovered by the Sloan Digital Sky Survey (SDSS) (York et al. 2000), namely: Ursa Major I and II (UMa II), Canes Venatici I (CVn I) and II (CVn II), Bootes I and II, Leo IV, Hercules, and Leo T (Willman et al. 2005; Zucker et al. 2006a,b; Belokurov et al. 2006, 2007; Walsh, Jerjen, & Willman 2007; Grillmair 2006; Irwin et al. 2007). Along with the 10 previously known MW dSph companions (Draco, Ursa Minor, Fornax, Carina, Sculptor, Leo I, Leo II, Sextans; Mateo 1998), and the two accreting systems, Sagittarius (Ibata, Gilmore, & Irwin 1995) and Canis Major (Martin et al. 2004), these new discoveries bring to twenty the number of dSph's surrounding the MW. The new dwarfs have half-light radii resembling those of the classical dSph's, however, they all have an effective surface brightness $\mu_V \gtrsim 28$ mag arcsec^{-2} (Belokurov et al. 2007), hence are fainter than the previously known LG dSph's. Their shapes are also quite irregular and there seems to be a correlation between irregularity and distance, as the closest ones (namely Bootes I, UMa II and Coma) appear to be more distorted, as if they were torqued by tidal interaction with the MW (Belokurov et al. 2006, 2007; Zucker et al. 2006b). All the new systems appear also to be rather metal-poor and to host a dominant old stellar population (Zucker et al. 2006a; Willman et al. 2005; Belokurov et al. 2006, 2007; Martin et al. 2007; Simon & Geha 2007).

CVn II (R.A. = $12^{\rm h}57^{\rm m}10^{\rm s}$, DEC = $34°19'15''$, J2000.0; $\ell = 113.6°$, $b = 82.7°$) is one

of the faintest of the newly discovered SDSS galaxies, with $M_V = -4.8 \pm 0.6$ mag and surface brightness ~ 29.5 mag arcsecond^{-2} (Belokurov et al. 2007). It is a low-mass ($[2.4 \pm 1.1] \times 10^6 M_\odot$; Simon & Geha 2007), compact dSph with a half-light radius r_h= $3.0' \pm 0.5'$ (Belokurov et al. 2007), corresponding to 132 ± 15 pc at a distance $d = 151^{+15}_{-13}$ kpc. The $i, g-i$ color-magnitude diagram (CMD) by Belokurov et al. (2007) shows that CVn II has a well-defined and narrow red giant branch and a horizontal branch (HB) that extends to the blue, through the RR Lyrae instability strip. Simon & Geha (2007) obtained spectra for 24 bright stars in CVn II, from which they derived a velocity dispersion of 4.6 ± 1.7 km sec^{-1} and an average metal abundance [Fe/H]=-2.31 ± 0.12 dex with a dispersion of $\sigma_{\rm [Fe/H]}$=0.47 dex using the Rutledge et al. (1997) technique, which provides metal abundances consistent with the Carretta & Gratton (1997) metallicity scale.

In this *Letter* we present a first CMD of the CVn II dSph galaxy in the B, V bands of the Johnson-Cousins photometric system, extending down to $V \sim 25.5$ mag and revealing the galaxy's main sequence turn off at $V \sim 24.5$ mag. We also provide light curves for two RR Lyrae stars we have identified in CVn II.

2. Observations and Data Reduction

Time-series B, V, I photometry of the CVn II dSph galaxy was collected in 2007, May 10-12, using the Prime Focus Imaging Camera (PFIP) of the 4.2m William Herschel Telescope (WHT), and the WIRO-Prime, the prime focus CCD camera (Pierce & Nations 2002) of the 2.3m Wyoming Infrared Observatory telescope (WIRO). The WHT and WIRO observations cover fields of view (FOVs) measuring approximately 16.2×16.2 arcmin^2 and 17.8×17.8 arcmin^2 in size, respectively, and allow us both to completely map the galaxy and to infer the contamination by field stars and background galaxies using an external area devoid of CVn II stars.

We obtained 30 V, 30 B and 15 I frames in total, corresponding to total exposure times of about 5 h, 5 h, and 2.5 h in V, B, and I, respectively. In this *Letter* we present results from the analysis of the B and V data.

Images were pre-reduced following standard procedures (bias subtraction and flat-field correction) with IRAF. We then performed PSF photometry with the DAOPHOT IV/ALLSTAR/ALLFRAI packages (Stetson 1987, 1994). The absolute photometric calibration was performed using standard stars in Landolt's (1992) field PG0918 observed at the WHT during the night of 2007, May 12. To derive individual calibration equations, all the PG0918 standards were observed in each of the two chips composing the PFIP camera. The atmospheric extinction

coefficients were calculated directly from the time-series observations of CVn II taken at different airmasses during the same night. A total number of 7 standard stars covering the color interval $-0.3 \lesssim B-V \lesssim 1.3$ mag were used to derive the calibration equations. The resulting scatter was less than 0.01 mag in both filters and for both chips of the WHT mosaic. Typical errors at the level of the CVn II HB ($V \sim 21.5$ mag) for the combined photometry of non-variable stars are (σ_V, σ_B) = (0.005, 0.01) mag and (σ_V, σ_B) = (0.01, 0.015) mag for the WHT and WIRO datasets, respectively.

3. Identification of the variable stars

Variable stars were identified from both the B and the V time series. First we calculated the Fourier transform (in the Schwarzenberg-Czerny 1996 formulation) for each star in the photometric catalog with at least 12 epochs, then we averaged this transform to estimate the noise and calculated the signal-to-noise ratios. The results in V and B were cross-correlated to eliminate spurious detections. We then checked all the stars with high S/N, and in particular all the stars around the HB. Since CVn II seems to host several blue straggler stars (BSS) (see §4) we also checked whether some of the stars in the BSS region might be variables of SX Phoenicis type. Possible candidates were found; however, no conclusive results were reached because of the severe aliasing problems caused by the data windowing. Study of the light curves and period derivation were carried out using GRaTiS (Graphical Analyzer of Time Series), which is proprietary software developed at the Bologna Observatory (see Di Fabrizio 1999; Clementini et al. 2000). We confirmed the variability and obtained reliable periods and light curves for 2 RR Lyrae stars: 1 fundamental-mode (RRab) variable with period $P = 0.743$ days, and 1 first overtone (RRc) star with period $P = 0.358$ days. Both stars lie within the half-light radius of the galaxy and fall on the HB of the CVn II CMD, thus strongly supporting their membership to the galaxy. Identification and properties of the confirmed variable stars are summarized in Table 1.

In the MW, GCs that contain significant numbers of RR Lyrae stars have the mean period of the fundamental-mode pulsators ($\langle P_{ab} \rangle$) either of about 0.55 days or of about 0.65 days, and separate into the so-called Oosterhoff I (Oo I) and Oosterhoff II (Oo II) types (Oosterhoff 1939). Extragalactic globular clusters and field RR Lyrae stars in dSph galaxies instead generally have the $\langle P_{ab} \rangle$ intermediate between the two types (Catelan 2004, 2005). The rather long periods of the RR Lyrae stars indicate that CVn II is an Oosterhoff type II system. So far, only two dSph galaxies of pure Oosterhoff type II had been known, namely Ursa Minor (UMi) among the traditional companions of the MW, and Bootes I (Dall'Ora et al. 2006; Siegel 2006) among the newly discovered SDSS dSph's. In terms of

RR Lyrae star properties, CVn II thus resembles UMi and Bootes I, and differs instead from CVn I, the brightest of the the SDSS dSph's, which has an Oosterhoff-intermediate type (Kuehn et al. 2007).

In Figure 2 we plot the CVn II RR Lyrae stars on the V and B period-amplitude diagrams of the Bootes I dSph galaxy, using data from Dall'Ora et al. (2006) and Siegel (2006). The position of the CVn II variables in Figure 2 confirms their similarity to the Bootes I RR Lyrae stars and supports the classification of CVn II as an Oosterhoff type II system.

4. The CMD and the galaxy structure

The $V, B-V$ CMDs of the CVn II dSph are shown in Figure 3, where we have plotted objects in the whole 16.2 × 16.2 arcmin^2 field covered by the WHT observations in panel a; only objects within the galaxy's half-light radius (r = 3.0′) in panel b; sources located in an annulus at 3.0′ $< r <$ 4.2′ in panel c; and, in panel d, sources located in an external annular region at 7.4′ $< r <$ 8.0′. The three regions cover areas in the ratio 1:1:1. Only stars with σ_V, $\sigma_B \leq 0.10$ mag , $\chi \leq 2$ are plotted in the figure. The solid and dashed lines are, respectively, the mean ridge lines of the Galactic GCs M15 (NGC 7078) and M3 (NGC 5272), drawn from the CMDs by Durrell & Harris (1993) for M15 and Buonanno et al. (1994) for M3, shifted in magnitude and color to match the CVn II horizontal and red giant branches. Adopting for the reddening of M15 $E(B-V) = 0.10\pm0.01$ mag (Durrell & Harris 1993), and for M3 $E(B-V) = 0.01\pm0.01$ mag (Harris 1996), the color shifts required to match the CVn II HB to those of M15 and M3 thus imply a reddening $E(B-V) = 0.015\pm0.010$ mag for CVn II. This is in agreement with the 0.014 ± 0.026 mag value derived for the galaxy from the Schlegel, Finkbeiner, & Davis (1998) maps. The CVn II CMD reaches $V \sim 25.5$ mag, and when considering the whole field of view of the WHT observations (Fig. 3a) appears to be heavily contaminated by field objects at every magnitude level. The HB of CVn II shows up quite clearly; however, the galaxy's red giant branch (RGB) is barely discernible from contaminating stars belonging to the MW halo and disk. Moreover, inspection of the frames reveals that CVn II is surrounded and partially embedded into clusters of background galaxies. In an attempt to separate stars from galaxies, we ran Source Extractor (SExtractor, Bertin & Arnouts 1996) on the WHT data. The morphological parameters of the detected sources allowed us to discriminate between point sources and extended objects for magnitudes brighter than $V \sim 24.4$ mag. The confirmed bona-fide stars are marked in blue and green in Figure 3. Figure 3b shows that the contamination by field sources can be significantly reduced if we consider only stars within the galaxy's half-light radius. Indeed, the features

of the galaxy's CMD show up much more clearly in Figure 3*b* and can be traced down to the main sequence turn off at $V \sim 24.5$ mag, where several stars are located in the BSS region (green dots in Fig. 3*b*), and are likely BSSs of CVn II. The HB and RGB of CVn II are very well reproduced by the CMD of the Galactic globular cluster M15, implying that CVn II has an old and metal-poor stellar population with metal abundance comparable to that of M15: $[Fe/H] = -2.15 \pm 0.08$ dex or -2.12 ± 0.01 dex on the Zinn & West (1984) and Carretta & Gratton (1997) scales, respectively. On the other hand, to match the M3 RGB would require a negative reddening for the cluster, and makes any metallicity spread as large as 0.5 dex or larger in CVn II unlikely, since the metallicity of M3 is $[Fe/H] = -1.66 \pm 0.06$ dex or -1.34 ± 0.02 dex on the Zinn & West (1984) and the Carretta & Gratton (1997) scales, respectively. Although SExtractor does not provide a reliable discrimination between stars and galaxies fainter than V=24.4 mag, Figure 3*b* suggests that many of the faint sources falling close to the ridge line of the M15 mean sequence are very likely main sequence stars of the CVn II dSph. Stars belonging to CVn II are still seen in Figure 3*c*; however, they appear to be rather few in number, thus indicating that the vast majority of the CVn II stars are confined within $r < 3.0'$ from the galaxy center. Finally, Figure 3*d* is a control field devoid of CVn II stars, and provides an indication of the degree of contamination by field stars and background galaxies in the region of the CVn II dSph.

We have used the mean ridge line of M15 as a reference to locate the stars most likely belonging to the CVn II galaxy in the CMDs of Figure 3. In Figure 4 we show the X,Y map of the sources that in the CMDs lie within ± 0.1 mag from the mean ridge line of M15 (stars are shown in blue, whereas objects classified by SExtractor as non-stellar or non-classified are shown in black) and of the stars with $V < 24.4$ mag in the region of the BSSs (green dots). Circles locate the 3 different areas corresponding to the CMDs in Figs. 3*b,c,d*. The bulk of the stars most likely to be members of the CVn II dSph is located within the inner circle of radius $r = 3.0$ arcmin, which corresponds to the galaxy's half-light radius. These stars outline a mainly circular structure perhaps slightly elongated in the South-West direction.

The strong similarity of the CMD to that of a simple population system like M15, the roughly spherical distribution of stars around the galaxy center (see Figure 4), and the compactness and relatively small size might suggest that CVn II is indeed a metal poor globular cluster, rather than an actual dSph galaxy. However, at a distance of 151 kpc (Belokurov et al. 2007), the half-light radius of CVn II corresponds to 132 pc, hence about 5-6 times larger than observed for NGC 2419, the largest of the Galactic GCs according to Bellazzini (2007). Such a large size is clearly inconsistent with the tight relation between size and galactocentric distance derived by van den Bergh (1995) for Galactic GCs, thus strongly disfavoring its GC classification.

5. An Improved Distance to the CVn II galaxy

The average apparent luminosity of the CVn II RR Lyrae stars is $\langle V \rangle = 21.48 \pm 0.02$ mag (average on 2 stars). Assuming M_V=0.59±0.03 mag for the absolute luminosity of the RR Lyrae stars at [Fe/H]=−1.5 dex (Cacciari & Clementini 2003), $\Delta M_V/\Delta[Fe/H]$=0.214 (± 0.047) mag/dex for the slope of the luminosity-metallicity relation (Clementini et al. 2003; Gratton et al. 2004), $E(B-V)$=0.015 mag, and [Fe/H]=−2.31 dex (Simon & Geha 2007), the distance modulus of CVn II is 21.02 ± 0.06 mag, which corresponds to a distance d=160^{+4}_{-5} kpc. Errors include the standard deviation of the mean, and the uncertainties in the photometry, reddening, and RR Lyrae absolute magnitude. This new, precise distance estimate agrees, within the uncertainties, with the distance of 151^{+15}_{-13} kpc found by Belokurov et al. (2007).

6. Summary and conclusions

We have identified and obtained B, V light curves for 2 RR Lyrae stars (1 RRc and 1 RRab) in the newly discovered CVn II dSph galaxy (Belokurov et al. 2007). The behavior of these two pulsators suggests an Oosterhoff II classification of CVn II. From the average luminosity of the RR Lyrae stars, the galaxy's distance modulus is μ_0=21.02 ± 0.06 mag ($d = 160^{+4}_{-5}$ kpc).

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Table 1: Identification and properties of the RR Lyrae stars in the CVn II dSph galaxy

Name	α (2000)	δ (2000)	Type	P (days)	Epoch(max) (-2450000)	$\langle V \rangle$ (a)	$\langle B \rangle$ (a)	A_V (mag)	A_B (mag)
V1	12 : 57 : 01.6	34 : 19 : 33.4	RRc	0.358	4232.854	21.49	21.74	0.678	0.832
V2	12 : 57 : 11.8	34 : 16 : 52.9	RRab	0.743	4231.504	21.46	21.77	0.707	0.952

[a] ⟨V⟩ and ⟨B⟩ values are intensity-weighted mean magnitudes.

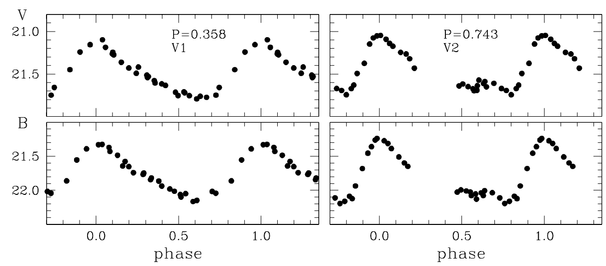

Fig. 1.— V and B light curves of the two RR Lyrae stars discovered in CVn II. *Left panels*: c-type RR Lyrae star; *right panels*: ab-type RR Lyrae star.

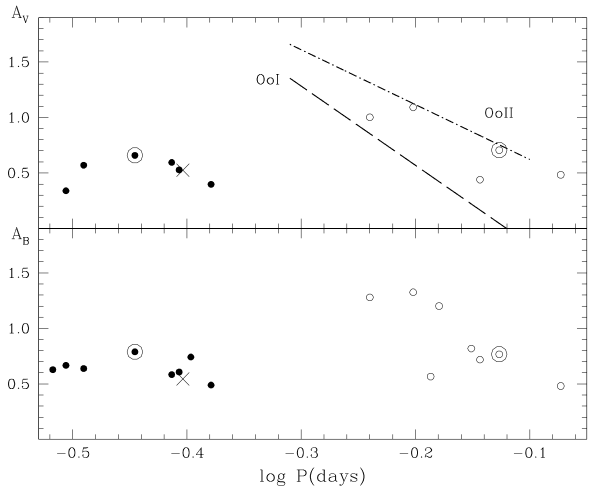

Fig. 2.— Position of the CVn II RR Lyrae stars (double circles) on the V and B period-amplitude diagrams of the Bootes I dSph variables. Open and filled circles are fundamental-mode and first-overtone pulsators, respectively. The cross is a double-mode variable. The two lines show the positions of Oo I and Oo II Galactic GCs according to Clement & Rowe (2000).

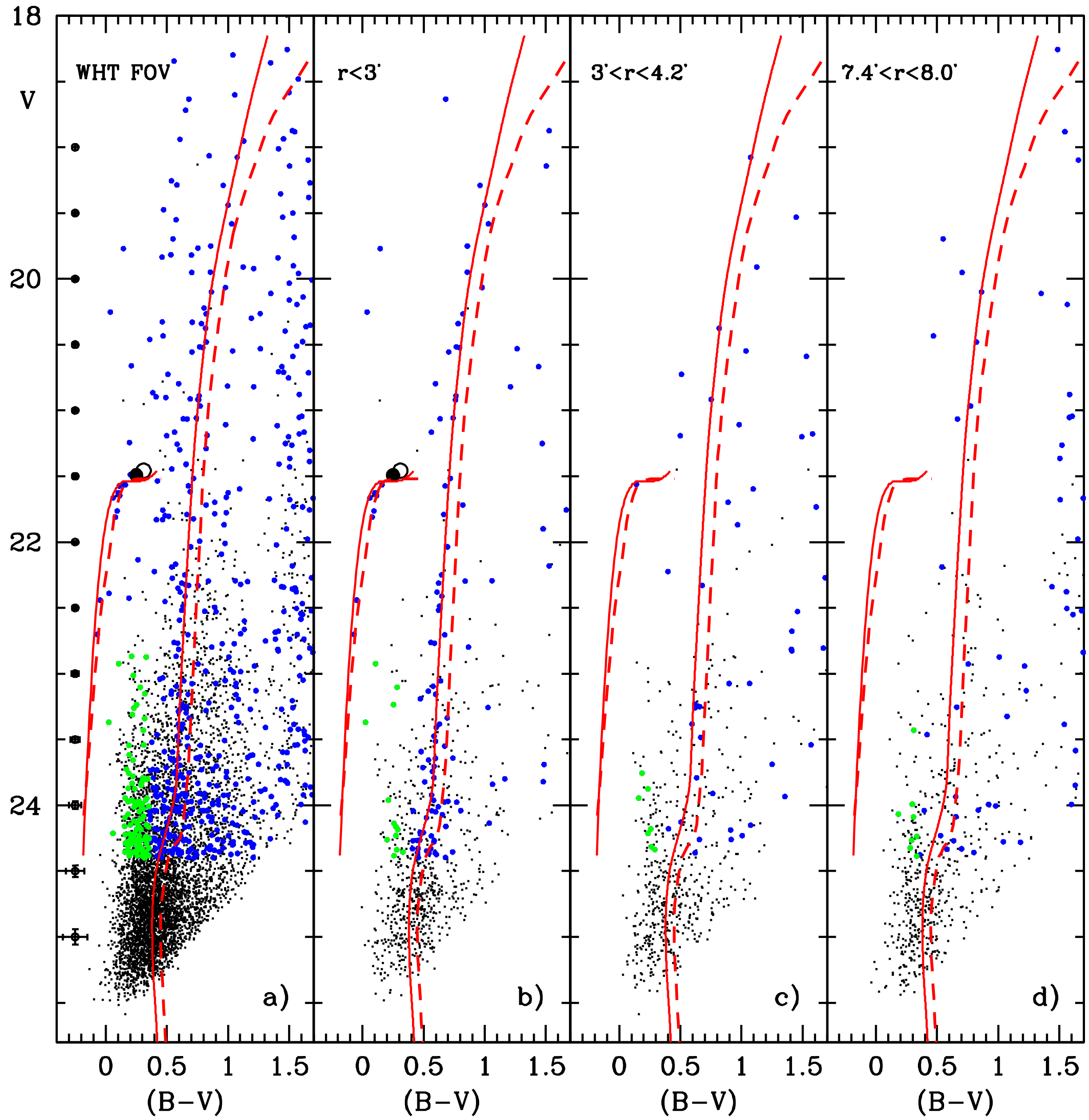

Fig. 3.— $V, B-V$ CMDs of the CVn II dSph, obtained from stars in the 16.2×16.2 arcmin^2 field covered by the WHT observations (panel *a*) and in 3 separate regions at increasing distance from the galaxy center (see labels). Sources that SExtractor confirmed to be stars are plotted in blue, the open circle is the ab-type RR Lyrae star and the filled circle is the c-type RR Lyrae star, whereas green dots are stars with $V < 24.4$ mag in the region of the BSSs. Solid and dashed red lines are the mean ridge lines of M15 and M3, shifted in magnitude and adjusted in reddening to fit the galaxy's horizontal and red giant branches. Typical error bars of the photometry are shown on the left-hand side.

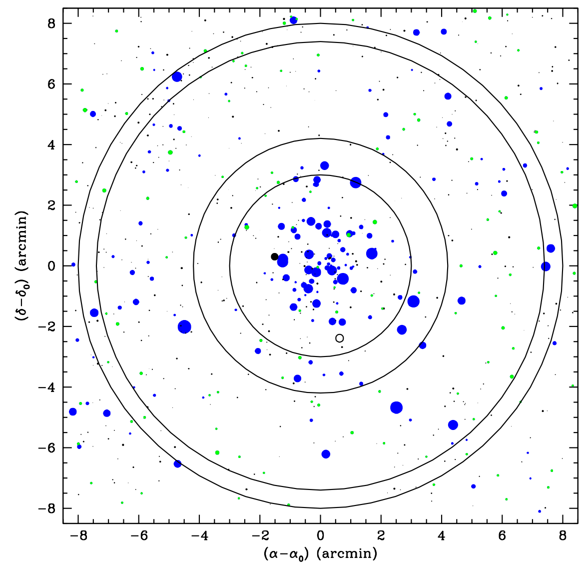

Fig. 4.— X,Y map, in differential R.A. and DEC (in arcmin) from the galaxy center, set at RA(J2000)= 12^h 57^m 10.1^s, DEC(J2000)=34° 19′ 13.5″, of sources that in Fig. 3a lie either within ± 0.1 mag from the mean ridge line of M15 or in the BSS region (green dots). Dot sizes are proportional to the objects' magnitudes with the largest dots corresponding to $V \sim$ 18-18.5 mag and the smallest ones to $V \sim 25$ mag. North is up and East to the left. Circles have radii of 3.0′, 4.2′, 7.4′, and 8.0′, respectively. Symbols and color-coding are as in Figure 3.